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(54) Title: ELECTRONIC TRACK DETECTION METHODS FOR APPARATUS FOR SIMULTANEOUSLY READING MULTIPLE ADJACENT TRACKS OF AN OPTICAL DISK
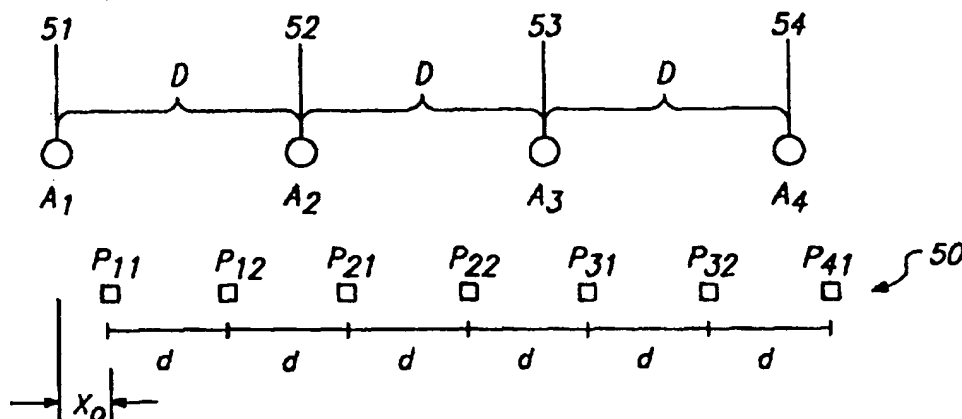
(57) Abstract

Methods and apparatus are provided for simultaneously tracking multiple data tracks of an optical disk using a detector matrix formed of a plurality of pixels. Based on track pitch, pixel pitch and predetermined point spread functions of the pixels, a series of simultaneous equations based on sampled pixel data is generated and solved to determine an offset distance between a selected pixel and a selected track and corrected values of the sampled pixel data. Alternatively, the series of equations may be generated, based on sample pixel readout values and a series of weighting coefficients, such that solution of the equations enables the position of a selected track to be determined.

ELECTRONIC TRACK DETECTION METHODS
FOR APPARATUS FOR SIMULTANEOUSLY READING
MULTIPLE ADJACENT TRACKS OF AN OPTICAL DISK

Field of the Invention

This invention relates to methods and
apparatus for retrieving information from an optical
disk by simultaneously reading multiple adjacent data
tracks, and more particularly to methods for
electronically tracking the location of multiple
adjacent data tracks on an optical disk.

Background of the Invention

Optical disks have become widely used in part
due to their relatively high storage capacity and long
storage life. Whereas a 3 1/2 inch floppy disk can
store 1.44 Mb (megabytes) of data, a 12 centimeter
compact (optical) disk can store upwards of 650 Mb.
Optical disks have therefore become increasingly
popular in recent years, with a number audio and
computer data storage products becoming commercially
available in a compact-disk (CD) optical disk format.
More recent developments in the application of optical
disk technology, such as the MultiMedia CD (MMCD)
developed by Sony Corp., the Super Density (SD) system
developed by Toshiba Corporation, and the new Digital
Video Disk (DVD) standard provide ever increasing
storage capacities.

A read-only compact disk (CD-ROM) generally
includes a 1.2 mm transparent plastic substrate having
data encoded in pits that are impressed into the
substrate along spiral or concentric data tracks on a
1.6 micron pitch. The pitted substrate is coated with
a reflective layer.

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To retrieve information from an optical disk, the disk is rotated and light is directed through the transparent substrate onto the reflective layer. The inhomogeneity created in the reflective surface by the pits causes light reflected from the pitted reflective surface to be of lower intensity, while the non-pitted reflective surface between the pits reflects almost all of the incident light. It is this modulation in light intensity that is used for information storage and retrieval.

Light reflected from the optical disk is directed to image detectors comprised of photosensitive elements that develop electronic signals corresponding to the intensity of the reflected light. These electronic signals are decoded by processing circuitry that recovers the digital information stored in the data tracks of the optical disk. Further details regarding the construction and use of optical disks in can be found in Compact Disc Technology, Nakajima, H. and Ogawa, H., translated by Aschmann, C., published by Ohmsha, Ltd., Japan (1992), and The Compact Disc Handbook, Pohlmann, K., 2d. ed., A-R Editions, 1992.

Because data is encoded sequentially along the data tracks of an optical disk, optical disk reading apparatus must be able to follow a particular track in order to be able to read the data encoded thereon. One of the problems encountered in reading data from an optical disk is that the data tracks typically exhibit eccentricity, which may cause the distance between a data track and the disk center to vary by as much as 70 microns. To read information from an optical disk, the apparatus must be able to accommodate this eccentricity during the retrieval of information.

In previously known optical disk readers, the image detector is mounted on an optical pickup which

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reads from one data track at a time. The optical
pickup typically includes lenses for focusing the light
from the light source to particular portions of the
disk surface, and for reflecting light from the
reflective disk surface to the image detector, as
described, for example, in the aforementioned Compact
Disc Technology text at Chapters 6 and 7, which are
incorporated herein by reference.

         In such previously known systems, tracking is
generally accomplished using the well-known "twin spot"
method, as described, for example, at pp. 133-136 of
the above-incorporated text. In this method, secondary
beams from the light source are projected onto the
optical disk ahead of and behind the main illumination
beam, and slightly off-axis from the main illumination
beam. Thus, tracking detectors associated with the
secondary beams "see" only the non-pitted reflective
surface of the optical disk when the main illumination
beam is centered over the data track. An error signal
is then developed as the difference between the signals
generated by the tracking detectors. That error signal
is provided to a servo-motor controlling movement of
the pickup.

         The increased availability of CD-ROM, and the
development of MMCD, SD and DVD products, coupled with
the availability of increasingly faster
microprocessors, has created the need for ever faster
optical disk drives. As a result, disk drives capable
of operating at multiples of a standard single speed
drive are becoming available, for example, 2X, 4X and
even 6X drives. For a 6X (six times single speed) disk
drive, the disk is rotated at speeds up to 2400 rpm
when reading the innermost data track.

         The ability to achieve even greater speeds
may soon be limited by the ability of such technology
to continue to provide low-cost, easily manufacturable

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systems, since the use of greater disk rotational
speeds will require more sophisticated, higher
tolerance, and thus more expensive, designs than
employed in previously known arrangements.

An alternative to simply increasing the disk
rotational speed is to read multiple data tracks
simultaneously, as described in commonly assigned U.S.
Patent No. 5,426,623, the entirety of which is
incorporated herein by reference. In accordance with
the methods and apparatus provided therein, for
example, ten adjacent data tracks may be read
simultaneously. Thus, even if the disk is rotated at
only twice standard speed (i.e., a 2X drive is used),
the capability to read multiple tracks provides the
equivalent of a 20X drive -- more than a factor of
three faster than previously known disk drives.

Implementation of simultaneous multiple track
reading capability for optical disks presents new
problems, however, relating to tasks such as focussing
and tracking. For example, with development of MMCD
and DVD formats, ever more data is being compressed
onto a single disk. Thus, for example, the track pitch
for the MMCD system is only about one-half that of the
CD-format, and includes shorter pit lengths and faster
rotation speed that increase the linear velocity from
about 1.4 m/s to 4 m/s.

In "Parallel Optical Memories", BYTE
magazine, September 1992, at p. 179, by Demetri
Psaltis, a system is described which enables parallel
access to optical disk tracks using a CCD detector to
receive images formed by a wide-area illumination beam.
As also described in "Optical memory disks in optical
information processing", Applied Optics, Vol. 29, No.
14, May 10, 1990, by Demetri Psaltis, and in U.S.
5,111,445, this system encodes information in different
formats in radial and tangential directions on the

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optical disk, so that it may be decoded without the aid
of focussing optics.

In view of the foregoing, it would be
desirable to provide improved electronic tracking
methods and apparatus, for use with apparatus capable
of simultaneously reading multiple data tracks using an
image detector, that generate an electronic tracking
signal based on the output of the image detector.

It further would be desirable to provide
improved electronic tracking methods and apparatus, for
use with apparatus capable of simultaneously reading
multiple data tracks, that reduces cross-talk in the
signals representative of data contained in adjacent
data tracks of the optical disk.

It would be yet further desirable to provide
improved electronic tracking methods and apparatus, for
use with apparatus capable of simultaneously reading
multiple data tracks, that permits reduction in the
data readout error rate.

Summary of the Invention

In view of the foregoing, it is an object of
this invention to provide improved electronic tracking
methods and apparatus, for use with apparatus capable
of simultaneously reading multiple data tracks using an
image detector, that generate an electronic tracking
signal based on the output of the image detector.

It is a further object of the present
invention to provide improved electronic tracking
methods and apparatus, for use with apparatus capable
of simultaneously reading multiple data tracks, that
reduces cross-talk in the signals representative of
data contained in adjacent data tracks of the optical
disk.

It is another object of this invention to
provide improved electronic tracking methods and

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apparatus, for use with apparatus capable of
simultaneously reading multiple data tracks, that
permits reduction in the data readout error rate.

These and other objects of the invention may
be accomplished in accordance with the following
methods and apparatus, suitable for use with multiple
track reading apparatus as described in U.S. Patent No.
5,426,623, which is incorporated herein by reference in
its entirety, or in concurrently filed, copending and
commonly assigned PCT application Serial No. _____
claiming the priority of U.S. patent application Serial No.
08/559,429 (ZRI-004; A 2925 PCT).

In accordance with the principles of this
invention, for an optical disk having distance D
between track centers, and disk reading apparatus
including an image detector formed of a matrix of
pixels having a distance d between centers, each with a
predetermined point spread function ("PSF"), a series
of simultaneous equations may be generated based on
sampled pixel data. This series of equations, when
solved, provides an offset value X_0 and the corrected
values of the image data corresponding to the tracks
read by the image detector. An electronic tracking
function may then be implemented by correcting the
optical pickup head position to maintain the offset
value X_0 at a given value.

Further in accordance with the present
invention, a series of equations may be generated,
based on sample pixel readout values and a series of
weighting coefficients, such that, when simultaneously
solved using linear algebraic or iterative techniques,
the position of a selected track I_0 may be determined.
By continually updating this analysis, the position of
optical pickup head may thereafter be adjusted to
maintain its position relative to track I_0.

The present invention also provides for
computing minimum values of the weighting coefficients

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used to determine track location, and for obtaining the
minimum value after integrating the image detector
signals over a plurality of time intervals.

Further features of the invention, its nature
and various advantages will be more apparent from the
accompanying drawings and the following detailed
description of the preferred embodiments.

Brief Description of the Drawings

FIG. 1 is an illustrative block diagram of a
multiple track reading apparatus constructed in
accordance with the present invention;

FIG. 2 illustrates the positioning of data
spots located on an optical disk and track boundaries
projected onto the pixels of a detector matrix of the
apparatus of FIG. 1;

FIGS. 3A and 3B provide illustrative   .
arrangements of a series of tracks in an optical disk
correlated to a line of starting pixels of an imaging
detector;

FIG. 4 shows illustrative radiation patterns
impinging upon a row of pixels in a detector matrix
used for imaging adjacent tracks of an optical disk;
and

FIG. 5 is a block diagram of processing
circuitry suitable for implementing the methods of the
present invention.

Detailed Description of the Invention

Referring to FIG. 1, apparatus 10 for
simultaneously reading multiple data tracks in
accordance with a preferred embodiment of the present
invention is described. Apparatus 10 includes
illumination source 12, optical system 14, detector
matrix 16 and image processing unit 18. Illumination
source 12 projects a wide-area beam of illumination

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towards optical system 14, which is projected onto an information bearing surface of optical disk 100.

Optical system 14 illustratively includes beam splitter 20, objective lens 22 and tube lens 24. Beam splitter 20 permits the wide-area illumination beam from illumination source 12 to be projected on optical disk 100, while the light reflected from optical disk 100 to beam splitter 20 is directed to tube lens 24. The light beam passing through tube lens 24 is directed to image detector 16.

Image detector 16 comprises a plurality of picture elements (pixels) arranged in a form of a matrix. Preferably, image detector 16 is of the charge-coupled device (CCD) or CCD time-integration delay (CCD/TDI) type, as described, for example, in commonly assigned U.S. Patent No. 5,426,623, the specification of which is incorporated herein by reference. Image detector 16 is positioned within the focal plane of optical system 14, so that the light beam projected on image detector 16 is converted to electric signals representative of the information bearing pits located on optical disk 100. The electric signals generated by image detector 16 are then processed in image processing unit 18, in accordance with the present invention, to provide readout and tracking of the data on optical disk 100.

As illustrated in FIG. 1, optical disk 100 comprises a plurality of information-bearing pits 101 arranged in circular or spiral tracks. When optical disk 100 is imaged by optical system 14 onto image detector 16, a single track (or pit within a track) is imaged by at least one pixel. In a preferred embodiment of the invention, each information bearing pit in a track is imaged by 3 to 4 pixels.

When optical disk 100 is rotated, information bearing pits ("data spots") 101 are swept along a

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direction perpendicular to the direction of the line of
pixels in the image detector. In a CCD/TDI image
detector, such as described in the above-incorporated
patent, this direction corresponds to the TDI
direction. During rotation, light collected from the
pixels in the CCD/TDI image detector (along the TDI
direction) is accumulated. The output of the signals
from these pixels may be used to develop a
representation of the location of the track and
between-track portions of optical disk 100.

        Referring now to FIG. 2, correspondence
between the positions of the data spots on optical disk
100 and the pixels of image detector 16 is described.
Data spot 30 is imprinted on track 32 having boundaries
34 imaged by several pixels in line of pixels 36. In
practical optical systems, a certain amount of "smear"
in the image is created due to diffraction effects;
irregularities in optical system 14, and noise in image
detector 16. This smear may be expressed in terms of a
Point Spread Function ("PSF"), which typically takes
the form of a Gaussian function, and represents the
optical response of a pixel as a function of the
distance from the mid-point of the pixel. The PSF for
each pixel generally is available either from the
manufacturer of the detector matrix, or may be
determined by testing.

        Due to the proximity of the tracks one to
another (generally a pitch of about 1.6 μm in CD-ROMS
and about 0.84 μm in the proposed MMCD format) and the
image smear, any pixel in the line of pixels 36, such
as pixel 38, may collect radiation from at least two
neighboring data spots, such as data spots 40 and 42.

        Pixel 38 may also collect radiation from data
spots in more distant tracks, such as data spots 30 and
44. However, the contribution of second order
neighboring data spots, such as spots 30 and 44, or

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higher order neighbors, is smaller than the
contribution of the first order neighboring spots.
Consequently, for any pixel, the contributions of
neighboring data spots depends upon the PSF of the
pixels, and on the lateral distance of the neighboring
data spots from that pixel.

Since the contributions of immediately
neighboring data spots may be significant, failure to
include these contributions may cause misalignment of
tracks, resulting in discontinuous track readouts, as
well as the mis-detection of non-data spots as data
spots. In such cases significant readout errors are
generated and the read-data error rate is increased.
The present invention is therefore directed to
providing methods for modifying the readout values of a
pixel to enable accurate tracking and reading by
verifying contributions of signals received from data
spots in the vicinity of a pixel.

Referring now to FIGS. 3A and 3B, the present
invention is illustratively described in the context of
detector matrix 16 as described hereinabove. The
methods described hereinafter are equally applicable to
any line of pixels in a detector matrix; to simplify
the following discussion, only the first line of pixels
of the detector matrix is discussed.

In FIGS. 3A and 3B, an individual pixel in a
line of pixels 50 of the detector matrix is indicated
by an integer number j, wherein $j=1,...,N$. The
distance between the centers of any two adjacent pixels
along line of pixels 50 in the detector matrix is
indicated by d, and d is assumed to be a known constant
value. The value of d is generally known from the
manufacturer's specifications for the detector matrix,
or may be determined by inspection of the detector
matrix. Alternatively, if d varies, a table of values
of d may be generated for the detector matrix and the

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appropriate values used in the equations described
hereinbelow.

Tracks 51, 52, 53 and 54 are indicated by an
integer number i, wherein i=1,...,K and K is the total
number of tracks. The distance between the center of a
track and the center of an adjacent track along a
radius in the optical disk, which is typically equal to
the track pitch, is indicated by D. Generally, the
position of the tracks and the pixels is not
correlated, so that at least part of the tracks is not
directly viewed by the pixels. While the track pitch
may vary due to inaccuracies in production processes,
it may be assumed that the change in track pitch in any
group of 4-5 consecutive tracks is not substantial, so
that D may be taken as constant over a group of 4
tracks. Alternatively, as described below, the methods
of the present invention may be extended to handle
cases where D varies.

The distances d between the centers of two
pixels and the distance D between the centers of two
tracks may also be considered in terms of spatial
frequencies, where a spatial frequency is defined by an
inverse of the distance between two points. Thus, the
pixels have corresponding spatial frequency of $1/d$ and
tracks have a spatial frequency of $1/D$.

Referring again to FIG. 3A, every pixel j in
the line of pixels has a readout signal $P_{i,j}$ that
depends upon the track i being imaged. This readout
signal also includes contributions from tracks which
are adjacent to track i. Readout values $P_{i,j}$ are time
dependent and vary as the tracks are rotated past the
detector matrix.

Data spot signals are indicated by A_i, where
i=1,...K indicates the track number. Accurate tracking
and detection requires that the position of a group of
tracks be correlated with the position of a group of

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pixels to determine the values A_i. The correlation
between a group of tracks and a group of pixels may be
expressed in terms of a lateral offset distance X_0 (see
FIG. 3A) between a pixel in the line of pixels and a
corresponding imaged track.

In accordance with the methods of the present
invention, offset distance X_0 and the values A_i are
determined for each group of tracks. These methods are
applicable to groups of tracks having a constant pitch
(i.e., distance between centers of two adjacent
tracks), as well as to groups of tracks in which the
track pitch varies between centers of any two adjacent
tracks in a group. Once the value of X_0 is known, the
location of other tracks may be computed based on X_0
and the track pitch D.

In FIG. 3A, tracks A_1-A_4 having a pitch D are
imaged by two pixels per track, the pixels having a
distance d between centers and readout values of Pi,j,
respectively. Thus, for example, track A_1 is
represented by readout signals P_{11} and P_{12}. Given that
the track pitch D and the PSF of the pixels is either
known or measured and computed at the beginning of the
readout process, and that the distance d is known from
the specific design of the detector matrix, the value
of the offset distance X_0 and values of three selected
adjacent data spot signals A_{INT}, A_{INT+1} and A_{INT+2} (where
INT is an integer having a value between 1 and one-
half of the number of pixels in the line of pixels),
may be found from the following set of equations:

for k=INT,

(1) A_k * PSF$[X_0 + (2*k-2)*d - (k-1)*D] + A_{k+1}$ *
            PSF$[k*D - X_0 - (2*k-2)*d] = P_{k,1}$

(2) A_k * PSF$[X_0 + (2*k-1)*d - (k-1)*D] + A_{k+1}$ *
            PSF$[k*D - X_0 - (2*k-1)*d] = P_{k,2}$

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and for k=INT+1

(3) A_k * PSF$[X_0$ + (2*k-2)*d - (k-1)*D] + A_{k+1} *
       PSF[k*D - X_0 - (2*k-2)*d] = $P_{k,1}$

(4) A_k * PSF$[X_0$ + (2*k-1)*d - (k-1)*D] + A_{k+1} *
       PSF[k*D - X_0 - (2*k-1)*d] = $P_{k,2}$

where k is an index having an integer value
between 1 and one-half of the number of pixels in the
line of pixels, and $P_{k,1}$, $P_{k,2}$, with k having values as
indicated in equations (1) - (4), are sampled pixel
readout values. The values 1 or 2 of the second index
of the readout values $P_{k,1}$, $P_{k,2}$ refer to whether the
readout signal originates from either the first or
second pixel positioned between the two adjacent
tracks.

For example, application of equations (1) -
(4), to a selected line of pixels for INT=1 results in
the following set of equations:

(5) A_1 * PSF(X_0) + A_2 * PSF(D-X_0) = $P_{1,1}$

(6) A_1 * PSF(X_0+d) + A_2 * PSF(D-X_0-d) = $P_{1,2}$

(7) A_2 * PSF(X_0+2*d-D) + A_3 * PSF(2*D-X_0-2*d) = $P_{2,1}$

(8) A_2 * PSF(X_0+3*d-D) + A_3 * PSF(2*D-X_0-3*d) = $P_{2,2}$

from which the values of X_0, A_1, A_2 and A_3 may be
obtained.

Since equations (1) - (4) form a set of 4
equations with 4 variables, the equations may be solved
simultaneously using linear algebra or an iterative
numerical technique for the values of X_0, A_{INT}, A_{INT+1}
and A_{INT+2}. Thus, the offset distance X_0 and the true
data signals A_{INT}, A_{INT+1} and A_{INT+2} can be determined.
The value of the data spot signals of the other tracks
also may be found by solving at least one of equations
(1) and (2) at respective values of k. Thus, for
example, once X_0, A_1, A_2 and A_3 are known from equations
(5) - (8), A_4 may be found by solving equations (1) or

(2) with INT=3. The same is applicable for the rest of
the tracks.

As will of course be appreciated, if the PSFs
of the pixels are not equal, the PSF employed in each
of the equations (1) - (4) will be different, but may
be obtained by measurement of the PSF of each pixel
prior to performing the readout process. Also, if the
distances between centers of adjacent tracks are not
constant, the exact values X_0 and A_i, i=1,...,K may
still be found by providing additional samples per
track, i.e., sampling a track with at least 3 pixels
instead of 2 pixels as illustrated in Fig. 3B.

Referring now to FIG. 3B, modified forms of
equations (1)-(4) for use when imaging a track with
line of pixels 60 having three pixels per track and
variable track pitches D_1, D_2,...,D_n, where n is an
index having integer values between 1 and K-1, are
described. In this case the value of the offset
distance X_0, the values of three selected adjacent data
spot signals A_{INT}, A_{INT+1} and A_{INT+2} (where INT is an
integer having a value between 1 and one-half of the
number of pixels in line of pixels 60), and the values
of D_n, for n=1,k with k being an integer having the
values between 1 and INT+1, may be found from the
following set of equations:

for k=INT

$$(9) \quad A_k * PSF[X_0 + (3*k-3)*d - \Sigma D_{n, \, n=1,k-1}] + A_{k+1} * PSF[\Sigma D_{n, \, n=1,k} - X_0 - (3*k-3)*d] = P_{k,1}$$

$$(10) \quad A_k * PSF[X_0 + (3*k-2)*d - \Sigma D_{n, \, n=1,k-1}] + A_{k+1} * PSF[\Sigma D_{n, \, n=1,k} - X_0 - (3*k-2)*d] = P_{k,2}$$

$$(11) \quad A_k * PSF[X_0 + (3*k-1)*d - \Sigma D_{n, \, n=1,k-1}] + A_{k+1} * PSF[\Sigma D_{n, \, n=1,k} - X_0 - (3*k-1)*d] = P_{k,3}$$

and for k=INT+1

(12) A_k * PSF[X_0 + (3*k-3)*d - $\Sigma D_{n, n=1,k-1}$] + A_{k+1} *
     PSF[$\Sigma D_{n, n=1,k}$ - X_0 - (3*k-3)*d] = $P_{k,1}$

(13) A_k * PSF[X_0 + (3*k-2)*d - $\Sigma D_{n, n=1,k-1}$] + A_{k+1} *
     PSF[$\Sigma D_{n, n=1,k}$ - X_0 - (3*k-2)*d] = $P_{k,2}$

(14) A_k * PSF[X_0 + (3*k-1)*d - $\Sigma D_{n, n=1,k-1}$] + A_{k+1} *
     PSF[$\Sigma D_{n, n=1,k}$ - X_0 - (3*k-1)*d] = $P_{k,3}$

where $P_{k,1}$, $P_{k,2}$, $P_{k,3}$ with k having the values as
mentioned in equations (9) - (13), are sampled pixel
readout values. The values 1, 2 or 3 of the second
index of the readout values $P_{k,1}$, $P_{k,2}$, $P_{k,3}$ refers to
the first, second or third pixel respectively,
positioned between two adjacent tracks. Equations
(9) - (13) form a set of 6 equations with 6 variables,
and therefore may be solved for the offset distance X_0,
the distances between the track centers D_n, l=1,INT and
the true data signals A_{INT}, A_{INT+1} and A_{INT+2}.

For example, equations (9) - (13) may be
applied to a selected line of pixels for INT=1 to
determine the values of X_0, D_1, D_2, A_1, A_2 and A_3. The
values of additional data spot signals and distances
between tracks then may be found by adding respective
equations. Thus, A_4 and D_3 for example, may be found by
solving the set of equations (9) and (10) with k=3, as
shown in the following equations:

(15) A_3 * PSF(X_0 + 6*d - D_1 - D_2) +
     A_4 * PSF(D_1 + D_2 + D_3 - X_0 - 6*d) = $P_{3,1}$

(16) A_3 * PSF(X_0 + 7*d - D_1 - D_2) +
     A_4 * PSF(D_1 + D_2 + D_3 - X_0 - 7*d) = $P_{3,2}$

The same solution technique may then be applied for the
rest of the tracks.

It is to be appreciated that all pixel
readout values $P_{i,j}$ and data spot signals A_i in

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equations (1) - (16) are time dependent. Accordingly,
the values of X_0, D_n, A_i determined from equations (1) -
(16) are time dependent and may be recalculated each
time the accumulated charge on the detector matrix is
sensed so as to provide accurate continuous tracking.

Comparison of equations (1) - (4) and (9) -
(14) shows that in general the system of equations may
be generally represented as:

$$P_j = \Sigma\ A_i\ *\ PSF_j(\delta_{i,j}),\quad \text{for all } i,\ j$$

wherein: P_j is an output of the jth pixel; A_i is a
signal representative of the data encoded in the ith
data track; PSF_j is the point spread function of the jth
pixel; and $\delta_{i,j}$ is the lateral distance between the ith
data track and the jth pixel.

For a constant inter-track spacing (track
pitch D), $\delta_{i,j}$ is defined as:

$$\delta_{i,j} = |X_0 + (mi-n)d - (i-1)D|$$

wherein: X_0 is the lateral offset distance between a
first one of the pixels and a first one of the adjacent
data tracks; m is the ratio of track pitch to pixel
pitch; n is given by the formula n = i mod j; d is the
pixel pitch; and D is the track pitch.

Alternatively, for a variable track pitch,
$\delta_{i,j}$ is defined as:

$$\delta_{i,j} = |X_0 + i*d - \Sigma D_k|,\quad \text{for all } k <= i$$

wherein: X_0 is the lateral offset distance between a
first one of the pixels and a first one of the adjacent
data tracks; d is the pixel pitch; and D_k is the
spacing between the kth and $k+1^{st}$ track.

In another aspect of the present invention,
an approximate correlation between the position of a

track and a pixel may be found. In this case, a pixel
is found which is nearest to a track, thus determining
the track position with a resolution corresponding to
the distance between the track and the nearest pixel.
Once the track positions are found, the true data spot
signals may be determined.

Every pixel j, where $j=1,\ldots,N$ is an integer
indicating a pixel number, has a readout signal P_j that
represents a component of the modulated light reflected
from neighboring tracks. The readout signal, or pixel
sample value P_j, therefore may be expressed in terms of
a summation, with different weights, over all
neighboring data spots. If a track data spot signal is
indicated by A_i, where $i=1,\ldots K$, is the number of
neighboring tracks, then for each pixel j the following
equation applies:

(17) $P_j = \Sigma \; \alpha(j,i) \; * \; A_i, \quad i=1,\ldots K$

where $\alpha(j,i)$ is a matrix of coefficients representing
different weight factors which are dependent upon the
pixels PSF's and the distance of a pixel j from a data
spot I. Coefficients $\alpha(j,i)$ are correlated with each
data spot signal A_i to provide the contribution of the
data spot signal to pixel j.

To provide accurate tracking during the
readout process of the optical disk, the position of a
selected track, indicated by I_0, must be determined.
Once the position of track I_0 is determined, the
positions of the other tracks are also known, assuming
equal spacing between tracks. If the distance between
the tracks is not equal, the position of each track
must be determined separately.

When the optical disk is sampled, values P_j
of a whole line of pixels are obtained. It is assumed
that one of the pixels, indicated by j_0, where j_0 is a

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value yet unknown, is the nearest to the center of the
selected track I_0. In order to determine the position
of track I_0, j_0 must be found.

If, as in one embodiment of a detector matrix
suitable for use with the present invention, a track is
sampled by 4 pixels, then a coefficient C, which
represents a first approximation to α, may be found by
computing the following minimum:

(18) $Min_j (P_j - C_0 * P_{j-2} - C_0 * P_{j+2})$

where the pixels j-2 and j+2 determine expected
boundaries of track I_0. As a first approximation,
$\alpha(j_0, i_0) = C_0$, and since variations in C_0 are small and
are mainly due to eccentricity of the optical disk,
there is no need to update C_0 at high sampling rates.

If equation (18) is solved for every pixel j,
j=1,...,N, then for each track I four different values
of C_0 are obtained, from which the value of C_0 is
selected which provides the lowest minimum value of
equation (18). On the other hand, if equation (18) is
solved for only part of the pixels, for example, every
four pixels, where a track is sampled by four pixels,
then only one value C_0 is obtained for each track.
However, greater confidence in the determination of the
tracks can be obtained by solving equation (18) for all
of the pixels in the line of pixels.

It will of course be understood that the
above-described method may be readily applied where a
different number of pixels is employed to image each
track. For example, if a track is sampled by 6 pixels,
then other pixels determine the boundaries of the
track, such as pixels j-3 and j+3 respectively, and six
different values of C_0 are obtained for each track,
when equation (18) is solved for all the pixels in a
line of pixels.

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Once the values of $\alpha(j,i)$ and P_j are known, the values of true data signals A_i for each track I may be factorized from the set of equations (17). Sensitivity tests may additionally be conducted on each C_0 value by altering the value of C_0 (which is factorized from equation (18)) by a small amount and checking if the result still provides the pixel i_0.

For higher accuracy, a series of C_0 values may be tested in order to provide the smallest minimum value in equation (18). It is to be appreciated that the smaller the minimum value in equation (18), the more accurate the tracking achieved. This testing may take the form of checking values in a range $C_0 + LL * \delta$ and $C_0 - LL * \delta$, and interpolating to find a best fit. In this case δ is a small value and LL is an integer value. LL may be either fixed or determined by the user. The result of these tests provides a best estimate for C_0 which may be different from the first selected value. In addition, equation (18) may be integrated over time before finding the minimum, so that sampling errors are smoothed and the results are more stable and accurate.

It is to be appreciated that the method described hereinbefore provides approximate values for each A_i. In particular, the method prevents the accumulation of errors caused by different spacing between tracks and allows accurate location of a plurality of tracks.

Referring now to FIG. 4, application of the method of track determination described hereinabove is illustrated. In FIG. 4, C_0 is taken as 0.5, wherein pixel Pj receives part of the radiation from a data spot in track i and part of the radiation from a data spot in track i+1. Pixels j-2 and j+2 image two tracks and have corresponding readout values of P_{j-2} and P_{j+2},

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respectively. The light reflected from tracks i and
i+1 produces radiation patterns 70 and 71,
respectively. Pixel j senses radiation which may be
less than the maximum values of radiation patterns 70
and 71.

Employing equation (18) with $C_0 = 0.5$ gives:

$$(19) \qquad Min\ (P_j - 0.5 * P_{j-2} - 0.5 * P_{j+2})$$

To search for the best fit, a set of
equations (19) is solved with P_j being replaced by P_{j-2}, P_{j-1}, P_{j+1} and P_{j+2}. In this set of equations, the
best fit is obtained for the pixel whose readout value
provides the lowest minimum value. For the arrangement
depicted in FIG. 4, the lowest minimum is obtained in
the equation for pixel readout value Pj, i.e. pixel j
images boundary point 72 and pixels j-2 and j+2 image
the two tracks respectively.

Sensitivity tests also may be performed by
testing a series of C_0 values, preferably around the
initial selection of $C_0 = 0.5$. In such a case, C_0 values
ranging from $C_0 - \epsilon$ and $C_0 + \epsilon$ (where ϵ is a small value)
may be tested and a C_0 whose value provides the lowest
minimum in equation (19) is selected. Additionally or
alternatively, the values of P_j, P_{j-2} and P_{j+2} may be
integrated over time before taking the minimum in
equation (18).

Referring now to FIG. 5, apparatus 80 for
enabling determination of the positions of tracks and
data spot signals in an optical disk readout system,
and implementing the methods described hereinabove, is
described. In a preferred embodiment, apparatus 80 may
form a part of image processing unit 18 of FIG. 1.

Apparatus 80 comprises difference calculator
82, integrator 84, sampler 86 and processor 88.
Difference calculator 82 receives pixel readout values

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Pj, j=1,..,N from detector matrix 16 (see FIG. 1) and
calculates equation (19) as described hereinabove. The
output of difference calculator 82 is a local minima at
a track boundary point, and is provided to integrator
84. Integrator 84 integrates the results of difference
calculator 82 over time (i.e., several samples) to
provide a stable minima.

The stable minima values of integrator 84 are
then provided to sampler 86 which outputs a time
varying sinewave-like function signal, compatible with
the stable minima values of integrator 84. The time
varying sinewave-like function signal is in turn
provided to processor 88, which calculates the minima
of time-varying function signal to determine the points
corresponding to the track boundaries. Once the
boundaries of a track are found, the track position is
determined.

Processor 88 calculates the offset distance
of each pixel from the nearest track and employs
previously measured PSF values, as described
hereinabove, to determine a set of coefficients $B(j,i)$
which are reciprocal to the coefficients $\alpha(j,i)$.
Coefficients $B(j,i)$ may be used for solving the
equation reciprocal to equation (17) to determine the
true data spot signals A_i. Processor 88 may be
implemented using a series of analog switches and
comparators, or alternatively, may comprise a general
purpose digital processor having digital switches.

While a preferred illustrative embodiment of
the present invention is described above, it will be
obvious to one skilled in the art that various changes
and modifications may be made therein without departing
from the invention and it is intended in the appended
claims to cover all such changes and modifications
which fall within the true spirit and scope of the
invention.

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What is Claimed Is:

1.   A method of simultaneously tracking
adjacent data tracks of an optical disk using a
detector matrix having a plurality of pixels, the
adjacent data tracks having locations and spaced apart
by a track pitch, each one of the plurality of pixels
generating a signal representative of a sum of
contributions from data stored in the adjacent data
tracks, the method comprising steps of:

generating a series of equations wherein the
signals for each one of the plurality of pixels
neighboring the adjacent data tracks are equated to the
contributions from the data stored in the adjacent data
tracks;

solving the series of equations to compute a
contribution for each one of the adjacent data tracks
and an offset distance between a selected one of the
plurality of pixels and a center of one of the adjacent
data tracks;

computing the locations of the adjacent data
tracks as a function of the offset distance and the
track pitch.

2.   A method as defined in claim 1 wherein
each one of the plurality of pixels has a location and
a point spread function, the plurality of pixels having
a pixel pitch, a predetermined number of the plurality
of pixels being spaced within the track pitch, and the
step of generating a series of equations further
comprises:

generating a series of equations equal in
number to the predetermined number of the plurality of
pixels spaced within the track pitch, each one of the
contributions being computed as product of a
coefficient representative of a corrected signal for

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each one of the adjacent data tracks and the point
spread function computed as a function of the track
pitch, the pixel pitch and the offset distance.

3.   The method as defined in claim 2 wherein
the step of solving the equations further comprises
determining the offset distance and the coefficient for
each one of the adjacent data tracks.

4. The method as defined in claim 2 or 3 wherein
the point spread functions for at least some of the
plurality of pixels differ.

5. The method as defined in claim 2, 3 or 4 wherein
the adjacent data tracks correspond to subsets of
multiple data tracks, and the track pitch varies across
a radius of the optical disk.

6. The method as defined in claim 2, 3, 4 or 5 further
comprising repeating the steps of generating, solving
and computing over a series of time intervals to track
the locations of the adjacent data tracks.

7. The method as defined in any one of claims 1 to 6
wherein the series of equations comprises:

for k=INT,

(I) $A_k * PSF[X_0 + (2*k-2)*d - (k-1)*D] +$
           $A_{k+1} * PSF[k*D - X_0 - (2*k-2)*d] = P_{k,1}$

(II) $A_k * PSF[X_0 + (2*k-1)*d - (k-1)*D] +$
           $A_{k+1} * PSF[k*D - X_0 - (2*k-1)*d] = P_{k,2}$

and for k=INT+1,

(III) $A_k * PSF[X_0 + (2*k-2)*d - (k-1)*D] +$
           $A_{k+1} * PSF[k*D - X_0 - (2*k-2)*d] = P_{k,1}$

(IV) $A_k * PSF[X_0 + (2*k-1)*d - (k-1)*D] +$
           $A_{k+1} * PSF[k*D - X_0 - (2*k-1)*d] = P_{k,2},$

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to provide values of the corrected signal A_{INT}, A_{INT+1} and A_{INT+2} for each one of the adjacent data tracks and X_0 is the offset distance between a first pixel in the plurality of pixels and a first of the adjacent data tracks, d is the pixel pitch, D is the track pitch, PSF is the point spread function of the respective one of the plurality of pixels, k is an integer index having a value of between 1 and one-half of the plurality of pixels, INT indicates a selected integer having a value of between 1 and one-half of the plurality of pixels, and $P_{k,1}$, $P_{k,2}$ are the signals for each one of the plurality of pixels neighboring the adjacent data tracks for each selected value of k.

8.   A method of tracking data tracks on an optical disk using a detector comprising a plurality of pixels, the data tracks having a track pitch, the plurality of pixels having a pixel pitch, wherein an output of each pixel is a function of an image of the optical disk projected onto the pixel, the image includes multiple adjacent data tracks, and wherein the pixel pitch is no more than one half the track pitch, the method comprising:

generating a series of simultaneous equations relating the outputs of the pixels to signals representative of data encoded in the multiple adjacent data tracks included in the projected image;

determining the output of each of the plurality of pixels; and

solving the series of simultaneous equations to extract the signals representative of the data encoded in the multiple adjacent data tracks from the outputs of the pixels.

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9.   The method as defined in claim 8 wherein
the step of generating the series of simultaneous
equations comprises deriving multiple equations of the
form:

$$P_j = \Sigma\ A_i * PSF_j(\delta_{i,j}), \quad \text{for all } i, j$$

wherein:

   P_j is an output of the jth pixel;

   A_i is a signal representative of the data
         encoded in the ith data track;

   PSF_j is a point spread function of a jth pixel; and

   $\delta_{i,j}$ is a lateral distance between an ith data
         track and a jth pixel.

   10. The method as defined in claim 9 wherein
the PSF is assumed to be zero for $\delta_{i,j} >$ the track
pitch.

   11. The method as defined in claim 9 or 10 wherein
P_j is an average output of a jth pixel.

   12. The method as defined in claim 9, 10 or 11 wherein
the pixel pitch is a constant.

   13. The method as defined in claim 12
wherein the track pitch is a constant and the step of
generating the series of simultaneous equations further
comprises deriving at least four equations and where

$$\delta_{i,j} = |X_0 + (mi-n)d - (i-1)D|$$

wherein:

   X_0 is the lateral offset distance between a
         first one of the pixels and a first one of
         the adjacent data tracks;

   m   is the ratio of track pitch to the pixel
         pitch;

   n   is given by the formula $n = i \bmod j$;

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d   is the pixel pitch; and

D   is the track pitch.

14.   The method as defined in claim 13
wherein each PSF_j is zero for $\delta_{i,j} > D$.

15.   The method as defined in claim 12, 13 or 14
wherein the track pitch is not constant and the step of
generating the series of simultaneous equations
comprises deriving at least six equations and further
comprises deriving equations of the form:

$$\delta_{i,j} = |X_0 + i \cdot d - \Sigma D_k|, \text{ for all } k <= i$$

wherein:

X_0 is the lateral offset distance between a
         first one of the pixels and a first one of
         the adjacent data tracks;

d   is the pixel pitch; and

D_k is the track pitch between a kth and a $k+1^{st}$
         track.

16.   The method as defined in claims 15
wherein each PSF_j is zero for $\delta_{i,j} > D_k$.

17.   A method for determining the location of
a data track of an optical disk relative to a plurality
of pixels of a detector matrix, the method for use in
an optical disk reading apparatus including the
detector matrix, the method comprising steps of:

generating with the plurality of pixels of
the detector matrix a series of pixel readout values
corresponding to a series of data spots on the multiple
tracks;

applying a selected preliminary weighting
coefficient to each one of the series of pixel readout
values for pixels neighboring a selected pixel;

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computing, for each one of the plurality of
pixels, a value corresponding to the readout value for
the respective pixel minus the sum, over all of the
pixels neighboring the respective pixel, of the product
of the selected preliminary weighting coefficient and
the respective pixel readout values;

determining a track location corresponding to
the location of the pixel for which the value is a
minimum.

18.   The method as defined in claim 17
wherein the minimum value is taken over a plurality of
pixels readout values at different times.

19.   The method as defined in claim 17 or 18
wherein the step of computing is performed over a
plurality of values in the vicinity of the selected ·
preliminary weight coefficient values to provide a
plurality of minimum values, and a lowest minimum value
from the plurality of minimum values is selected to
determine the track location.

20. The method as defined in claim 17, 18 or 19
wherein the minimum value is determined over an
integration of a plurality of pixel readout values at
different times.

21.   Apparatus for representing locations of
multiple adjacent data tracks of an optical disk
comprising:

optical means for providing an image of a
portion of multiple adjacent data tracks of the optical
disk;

an image detector comprising a plurality of
pixels onto which the image of the portion of multiple
adjacent data tracks is projected, the plurality of

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pixels having a pixel pitch and generating signals
representing data encoded on the optical disk;

means for processing the signals by
generating and solving a series of equations to
determine an offset value between a selected track and
a selected pixel of the plurality of pixels, and
corrected values of the signals corresponding to the
locations of the multiple data tracks; and

means for computing the locations of the
multiple data tracks based on the offset value and the
track pitch.

22.   Apparatus for representing locations of
multiple adjacent data tracks of an optical disk
comprising:

optical means for providing an image of a
portion of multiple adjacent data tracks of the optical
disk;

an image detector comprising a plurality of
pixels onto which the image of the portion of multiple
adjacent data tracks is projected, the plurality of
pixels generating signals representing data encoded on
the optical disk;

means for applying a selected preliminary
weighting coefficient to each one of the series of
pixel readout values for pixels neighboring a selected
pixel;

means for computing, for each one of the
plurality of pixels, a value corresponding to the
readout value for the respective pixel minus the sum,
over all of the pixels neighboring the respective
pixel, of the product of the selected preliminary
weighting coefficient and the respective pixel readout
values; and

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means for determining a track location
corresponding to the location of the pixel for which
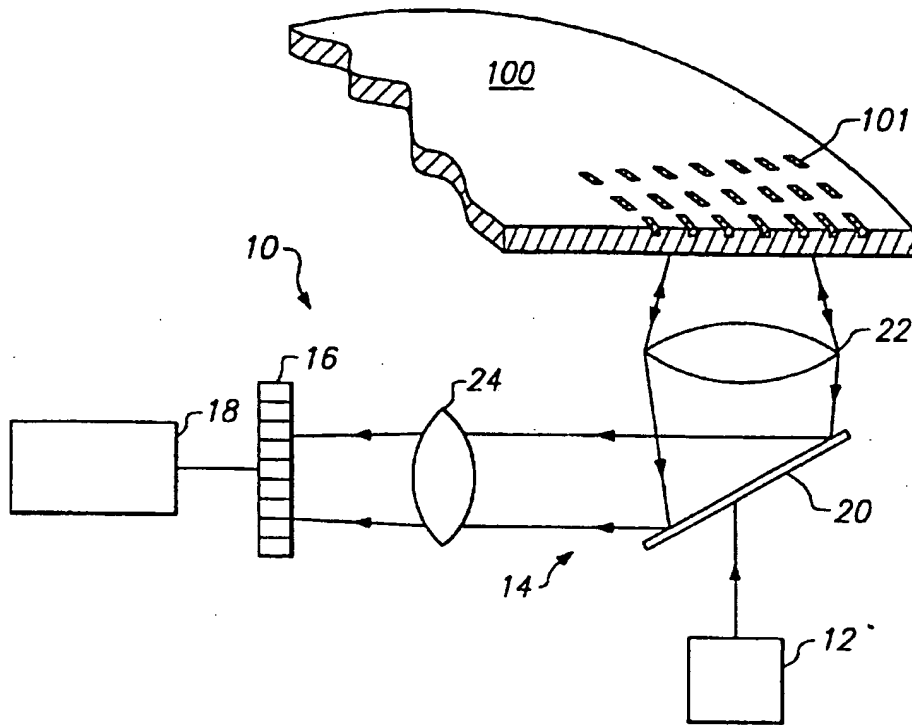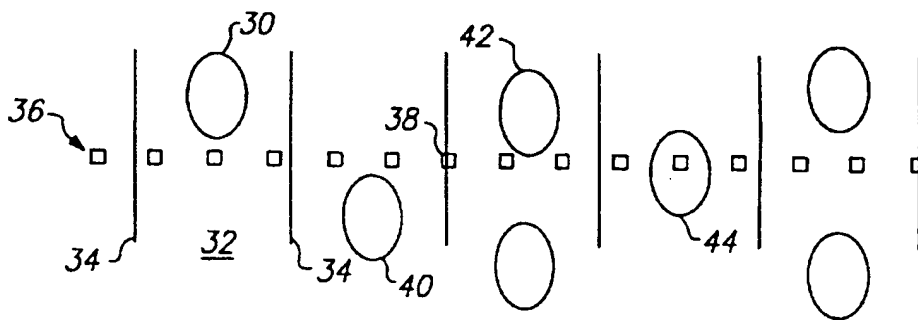the value is a minimum.

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FIG. 1

FIG. 2
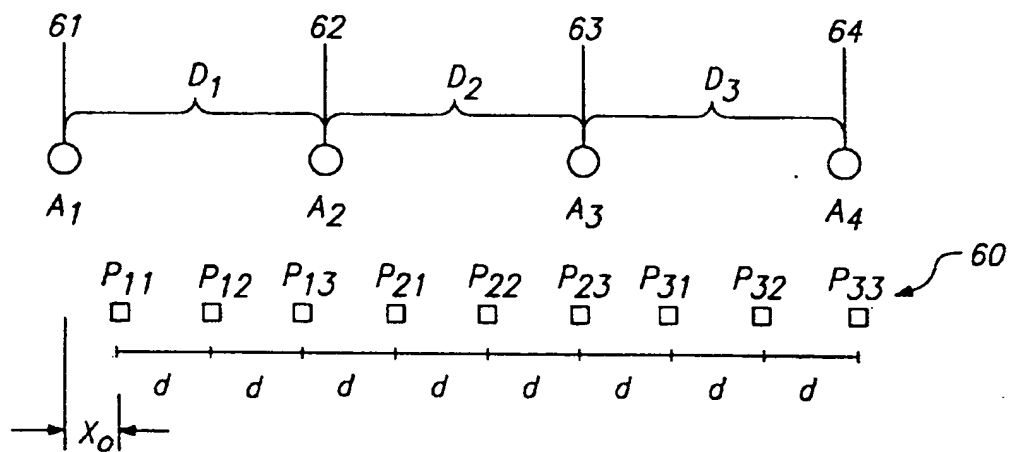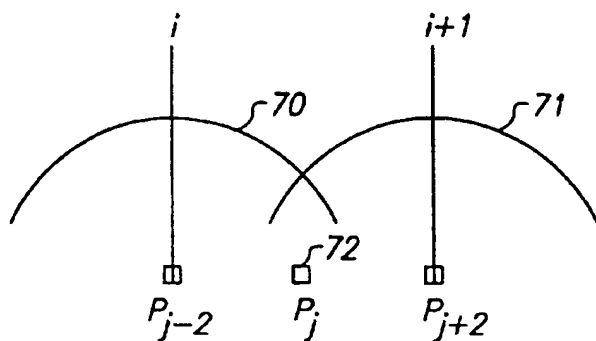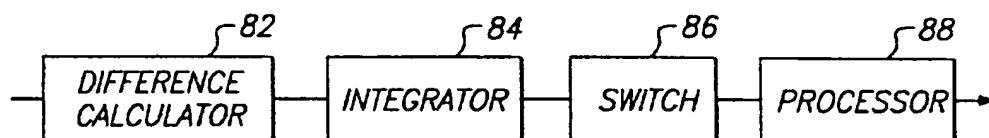
2/3

FIG. 3A
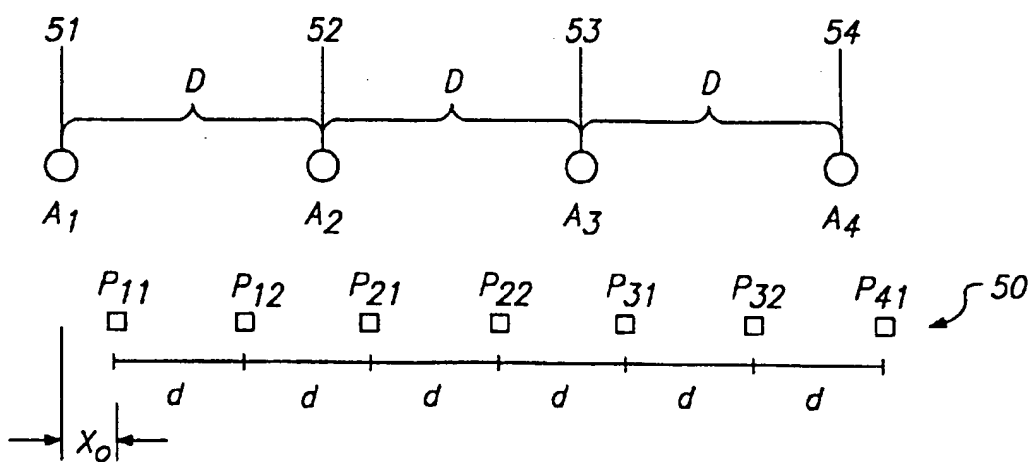

FIG. 3B

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i $i+1$

70

71

72

P_{j-2} P_j P_{j+2}

FIG. 4

| DIFFERENCE CALCULATOR ⌐82 | INTEGRATOR ⌐84 | SWITCH ⌐86 | PROCESSOR ⌐88 |

FIG. 5

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6   G11B7/09   G11B7/14   G11B7/00   G11B20/10   G11B20/22
        G11B21/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6   G11B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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A	see the whole document	1,21

Y	EP 0 400 899 A (PIONEER ELECTRONIC CORP) 5 December 1990	8,17,22
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A	US 3 780 266 A (MUDSAM U ET AL) 18 December 1973 see the whole document	1,8,17, 21,22

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[X] Further documents are listed in the continuation of box C.   [X] Patent family members are listed in annex.

* Special categories of cited documents :

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
25 March 1997	18. 04. 97

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl. Fax (+31-70) 340-3016	Nanos, A

Form PCT/ISA/210 (second sheet) (July 1992)

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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